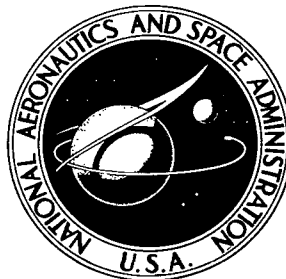


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FREQUENCY RESPONSE OF TWO TYPES
OF LIQUID-METAL PRESSURE
TRANSDUCERS WITH STANDOFF TUBES

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16. Abstract Frequency response tests were conducted on two types of pressure transducer systems commonly used in liquid-metal space power systems. Each transducer was an absolute pressure sensor with a range of 0 to 50.0 psia (0 to 34.5 N/cm ²). The tests were conducted using constant-diameter tubing (i.d., 0.187 in., 0.476 cm) ranging in length from 6 to 24 in. (15 to 61 cm). The process fluids were mercury and aliphatic petroleum naphtha solvent. The density and viscosity of these fluids are, respectively, for mercury, 48.93×10^{-2} lb/in. ³ (13.55 g/cm ³) and 1.54 centipoise (1.54×10^{-3} (N)(sec)/m ²), and for the naphtha solvent, 2.57×10^{-2} lb/in. ³ (0.71 g/cm ³) and 0.24 centipoise (0.24×10^{-3} (N)(sec)/m ²). Sinusoidal pressure fluctuations were applied at peak-to-peak pressure amplitudes of 5.0 psia (3.5 N/cm ²) generated at an average pressure level of 25.0 psia (17.3 N/cm ²) over a frequency range of 0.4 to 40 Hz. The data are presented in terms of amplitude ratio and phase angle as a function of logarithmic frequency. The results are cross-plotted to show natural frequency as a function of tube length. The data are also compared with theoretical predictions.					
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FREQUENCY RESPONSE OF TWO TYPES OF LIQUID-METAL PRESSURE TRANSDUCERS WITH STANDOFF TUBES

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SUMMARY

Frequency response tests were conducted on pressure transducer systems commonly used in the liquid-metal space program. The pressure transducer systems consisted of a transducer and a length of constant-diameter tubing (i. d. , 0.187 in. , 0.476 cm) connecting the transducer to the process fluid. Two types of transducers were investigated: slack bellows and a slack diaphragm with a capillary tube. Each transducer was an absolute pressure sensor with a range of 0 to 50.0 pounds per square inch absolute (0 to 34.5 N/cm²). Tests were conducted for four tubing lengths from 6 to 24 inches (15 to 61 cm) using mercury and aliphatic petroleum naphtha solvent as the process fluids. The density and viscosity of these fluids are, respectively, for mercury, 48.93×10⁻² pound per cubic inch (13.55 g/cm³) and 1.54 centipoise (1.54×10⁻³ (N)(sec)/m²), and for the naphtha solvent, 2.57×10⁻² pound per cubic inch (0.71 g/cm³) and 0.24 centipoise (0.24×10⁻³ (N)(sec)/m²). Sinusoidal pressure fluctuations were applied at peak-to-peak pressure amplitudes of 5.0 pounds per square inch absolute (3.5 N/cm²) generated at an average pressure level of 25.0 pounds per square inch absolute (17.3 N/cm²) over a frequency range of 0.4 to 40 hertz.

Data from the slack-bellows pressure transducer systems indicated decreasing natural frequency with increasing tube length. The natural frequencies ranged from 4.9 to 2.5 hertz using mercury and from 18.9 to 10.8 hertz using the naphtha solvent. These results were found to conform with the theoretical predictions. The maximum deviation between the experimental and theoretical results was less than 10 percent for both fluids. The frequency response characteristics of the slack diaphragm with capillary tube transducer systems were not affected by either standoff tube length or the fluid used.

INTRODUCTION

Among the numerous problems encountered in the development of space power systems and nuclear reactors which use liquid metals as heat-transfer mediums is the accurate measurement of pressure. Long-term reliability while operating in a high-temperature corrosive environment is a basic requirement for the pressure sensing instruments used in these systems. To meet this requirement, high-reliability pressure transducers have been used in conjunction with standoff tubes (ref. 1). The standoff tubes are used to reduce the temperature level at the sensing element by radiation along the tube length, as well as to permit access to the transducers after the piping insulation is installed. However, the combination of standoff tube plus instrument volume may not lend itself to the accurate measurement of pressure under transient conditions. In order to accurately interpret the measured readings for transient operation, it is necessary to know the frequency response of the pressure measuring systems.

Transducer frequency response information published in the manufacturer's specifications usually includes only the resonant frequency of the bare transducer alone. Mathematical methods for calculating the resonant frequency of the transducer-tubing combination are available (ref. 2); however, at the time of this work, these methods had not been verified with liquid metals. This report, therefore, presents the results of an experimental study to determine the frequency response of pressure transducer systems commonly used in liquid-metal space power systems. The effect of standoff tube length on the natural frequency of the transducer system was determined and compared with theoretical predictions.

Two types of transducers and two process liquids were used in the tests. The liquids used were mercury and an aliphatic petroleum naphtha solvent. The fluid properties of the latter liquid (density and viscosity) were similar to those of a eutectic mixture of sodium-potassium (NaK). Mercury and NaK are the working fluids of the SNAP-8 power system. The constant-diameter tubing ranged in length from 6 to 24 inches (15 to 61 cm).

The tests were conducted using constant-amplitude, variable-frequency, sinusoidal pressure fluctuations ranging in frequency from 0.4 to 40 hertz. The data are presented in terms of amplitude ratio and phase angle as a function of logarithmic frequency. The results are cross-plotted to show natural frequency as a function of standoff tube length. For the comparison with theoretical predictions, the theoretical method derived by R. C. Anderson of the NASA Lewis Research Center in an unpublished work is used.

APPARATUS AND PROCEDURE

Test Systems

The transducer systems consisted of a pressure transducer and a length of tubing (standoff tube) which connects the transducer to the process line. The tests were conducted at room temperature using 0.187-inch- (0.476-cm-) inside-diameter standoff tubes in lengths of 6, 12, 18, and 24 inches (15, 30, 46, and 61 cm). The process fluids were mercury and aliphatic petroleum naphtha solvent. The densities and viscosities are, respectively, for mercury, 48.93×10^{-2} pound per cubic inch (13.55 g/cm^3) and 1.54 centipoise ($1.54 \times 10^{-3} \text{ (N)(sec)/m}^2$), and for the aliphatic petroleum solvent, 2.57×10^{-2} pound per cubic inch (0.71 g/cm^3) and 0.24 centipoise ($0.24 \times 10^{-3} \text{ (N)(sec)/m}^2$). The petroleum solvent simulates a eutectic NaK mixture at approximately 1300° F (980 K).

Two types of pressure transducers were tested. Each was an absolute pressure sensor with a range of 0 to 50.0 pounds per square inch absolute (0 to 34.5 N/cm^2).

In one of the transducers tested, the process pressure is sensed by a slack bellows which is connected to a force rod that transmits the pressure to a series of calibrated force-balancing springs. The force rod extends through the force-balancing springs to the core of a linear-variable differential transformer (LVDT). The movement of the rod is thus converted to a 0- to 500-millivolt dc electrical output signal by the LVDT and its signal conditioner.

For the other transducer investigated, variations in fluid pressure are sensed by a slack diaphragm and transferred by a 10-foot- (3-m-) long NaK-filled capillary to a Bourdon tube located in a remote case. The motion of the Bourdon tube is coupled through suitable linkage to position a visual indicator and the core of an LVDT. The LVDT, with appropriate signal conditioning, converts the motion to a 100- to 500-millivolt dc electrical output signal.

Test Facility and Operation

Constant-amplitude, variable-frequency sinusoidal pressure variations were used for the input pressure. The pressure generator and test section are shown in the schematic cutaway of figure 1. The generator consists mainly of a piston-in-cylinder, a scotch-yoke mechanism machined into the piston and an adjustable eccentric. When the device is coupled to a variable-speed motor, the scotch yoke acts through the eccentric and transfers the rotary motion of the motor to the reciprocating motion of the piston. The displacement of the piston is simple harmonic, and thus the pressure variations in

the precharged cylinder are sinusoidal. The amplitude of the pressure variations is determined by the adjustment of the eccentric, and the frequency is determined by the speed of the motor.

As illustrated in figure 1, the transducer systems were attached to the test section and both were completely filled with the process fluid. The input pressure was generated in the gaseous medium (air) immediately above the liquid in the test section. The pressure was transferred by the liquid and was sensed by the transducer systems. Two reference transducers were used, one in the liquid, and one in the gas above the liquid. The transducer mounted in the gaseous medium was used only to show the actual output signal of the generator. Both reference transducers were of the flush-diaphragm, unbonded-strain-gage type with a range of 0 to 100 pounds per square inch absolute (0 to 69 N/cm²). The electrical output signal from each transducer was amplified by a differential-variable gain amplifier and was displayed on a multichannel, direct-recording oscillograph. Figure 2 is a photograph of the test facility.

Test Procedure

The standards established by the Instrument Society of America (ref. 3) were used as a guide for the test procedure. The procedure was as follows:

- (1) The input reference sine wave was generated at the midspan of the transducer being tested with a peak-to-peak amplitude of 10 percent of transducer span.
- (2) The tests began at a frequency low enough that the amplitude of the output sine wave (of the transducer being tested) was essentially equal to the amplitude of the input reference sine wave with no phase shift.
- (3) Frequency was increased in small increments until the amplitude of the output sine wave was 10 percent of the input reference sine wave.

For the 50.0-pound-per-square-inch-absolute (34.5-N/cm²) transducer systems under test, the input pressure had a peak-to-peak amplitude of 5.0 pounds per square inch absolute (3.5 N/cm²) at a pressure level of 25.0 pounds per square inch absolute (17.3 N/cm²) over a frequency range of 0.4 to 40 hertz. To obtain these values of amplitude and pressure level, the piston was set at midstroke and the cylinder was charged to 25.0 pounds per square inch absolute (17.3 N/cm²). The signal generator was then manually operated, and the eccentric was adjusted for a 5.0-pound-per-square-inch-absolute (3.5 N/cm²) peak-to-peak output. Once established, no further amplitude adjustments were made throughout the test. The cylinder was recharged (at midstroke) before each frequency setting to make up for any leakage past the seals.

It is important that the transducer systems be completely filled with liquid, since even the smallest amount of entrapped gas will affect dynamic response. To eliminate

entrapped gas, the transducer systems were hydraulically bled through a bleed valve located at the highest point in the transducer housing. As a check, two similar tests were run at different average pressure levels. The natural frequency of the transducer system was unchanged in each case indicating that the liquid in the system was free of voids significant to these tests.

Data Reduction Procedure

Typical oscillograph traces of the output signals are shown in figure 3. Figure 3(a) shows the signals with zero phase shift (0.05 Hz), the starting point for a particular test run. Figure 3(b) shows the output waveform at a higher frequency (10 Hz). Note the difference in amplitude and phase between the reference signals and the transducer system signals.

Measurements of amplitude ratio and phase shift were obtained by comparing data from the transducer systems to those from the liquid reference transducer. Amplitude ratio was determined from the relative peak-to-peak values. Phase shift was determined by measuring the displacement between waveforms on the time axis and converting to angular units:

$$\text{phase shift} = \frac{\text{distance between similar points on the wave} \times \text{frequency} \times 360^\circ}{\text{chart speed}}$$

Frequency was obtained by measuring the number of complete cycles per length and multiplying by chart speed. The amplitude ratios were normalized by dividing the amplitude ratios obtained at each frequency by the amplitude ratio obtained at the lowest frequency (zero phase shift). These parameters were used to construct frequency response curves of normalized amplitude ratio and phase shift as a function of logarithmic frequency. Where these curves indicated that the response of the transducer systems approximated that of a second-order system, the natural frequency was determined from the 90° phase lag point. Values of damping ratio (at these natural frequencies) were estimated by comparing the measured frequency response curves to the normalized frequency response curves for second-order systems shown in figure 4. For example, assume that the maximum amplitude ratio measured was 5.0. From figure 4 this value yields a damping ratio of 0.1.

In figure 4, for damping ratios less than 0.23 (which are typical of the slack-bellows transducer systems), the maximum amplitude ratio occurs at or near the resonant frequency so that measurements from transducer systems operating at the resonance frequency are inaccurate. The pressure readings lag the true pressures by 90° and are highly magnified. A more useful characteristic than resonant frequency is the

usable frequency range. The usable frequency range is expressed as the maximum frequency at which the system will perform within a given amplitude accuracy. For example, in figure 4, for transducer systems with damping ratios between 0.1 and 1.0, the pressure readings will be accurate within 10 percent to about one-third of the resonant frequency.

Measurements of amplitude, phase, and frequency taken from the oscillograph traces were made with a graduated scale (every 0.020 in., 0.050 cm). All measurements were made as accurately as possible, and the overall accuracy is assumed to be within 10 percent.

RESULTS AND DISCUSSION

Frequency response curves of the slack-bellows transducer systems with standoff tube lengths of 6, 12, 18, and 24 inches (15, 30, 46, and 61 cm) for both mercury and the simulated NaK (aliphatic petroleum naphtha solvent) are shown in figure 5. The data represent the total response of the liquid-filled transducer plus the liquid column in the standoff tube.

The shape of the curves approximates the response of a second-order system; therefore, the frequency at which 90° phase lag occurs was chosen as the system natural frequency. The damping ratios were estimated from a comparison of the measured maximum amplitude ratios with those in figure 4. The values of natural frequency f_n and damping ratio Z obtained with each fluid and tube length are listed in the following table:

Length		Mercury		Naphtha solvent	
in.	cm	Natural frequency, f_n , Hz	Damping ratio, Z	Natural frequency, f_n , Hz	Damping ratio, Z
6.0	15	4.9	0.14	18.9	0.23
12	30	3.5	.13	14.4	.17
18	46	3.0	.10	12.2	.14
24	61	2.5	.10	10.8	.11

As expected, system natural frequency decreases with increasing standoff tube length. The natural frequencies using mercury are considerably less than those using the solvent because of the difference in liquid densities. For any given condition, the more dense the liquid, the lower the natural frequency.

In the phase response curves, the data scatter beginning around 200° lag is probably the result of error in data reduction. The output amplitudes in this frequency range are attenuated to approximately 80 percent of the reference amplitude. Accurate phase shift measurements are difficult with such small amplitudes.

The resulting natural frequencies of these data are cross-plotted and shown as a function of standoff tube length in figure 6. Also plotted in figure 6 is the theoretical curve for each fluid obtained from the following equation:

$$f_n = \frac{D}{4 \sqrt{\rho \pi L \left(\frac{\Delta V}{\Delta P} \right)}}$$

where

f_n undamped natural frequency

D inside diameter of tube, 0.187 in. (0.476 cm)

ρ fluid density

L tubing length, 6 to 24 in. (15 to 61 cm)

$\frac{\Delta V}{\Delta P}$ transducer volumetric displacement with pressure, 4.1×10^{-3} in.³/psia
(9.7×10^{-2} cm³/(N/cm²))

The density of mercury is 48.93×10^{-2} pound per cubic inch (13.55 g/cm³), and the density of the solvent is 2.57×10^{-2} pound per cubic inch (0.71 g/cm³). The equation is taken from an unpublished work by R. C. Anderson of the NASA Lewis Research Center and assumes that the system is equivalent to a simple mass-spring analogy. Anderson goes on to refine the equation to include the spring effect from the compressibility of the liquid in the transducer volume, as well as tubing end effects. However, for the slack-bellows transducer systems tested, these terms were found to be negligible.

The curves show that the experimentally obtained resonant frequencies of these transducer systems, when used with liquids typical of those used in space power systems, do conform to theoretical predictions. The maximum deviation between experimental and theoretical results was less than 10 percent. The effects of fluid density and tubing length can readily be determined from figure 6. For a given standoff tube, the natural frequency varies as the square root of the inverse of the density ratio; and for constant density (and tubing i.d.), the natural frequency varies as the square root of the inverse of tubing length.

The frequency response of the slack diaphragm with capillary tube transducer systems for both mercury and the aliphatic petroleum naphtha solvent is shown in figure 7. The amplitude ratio curves for each fluid show that the response is essentially identical for all tube lengths and fluids tested.

The amplitude curves also show that there are two resonant peaks followed by abrupt attenuation. The two peaks are probably due to resonances in the NaK-filled capillary system. They occur at the same frequencies in each case, and these frequencies are well below the resonant frequencies expected for the portion of the transducer system that includes the standoff tube and slack diaphragm. In the frequency range where the effects of tube length and density should occur, the effects were masked by the strong attenuation, evidently from the capillary tube system.

SUMMARY OF RESULTS

The results of the frequency response tests conducted on two types of liquid-filled pressure transducer systems may be summarized as follows:

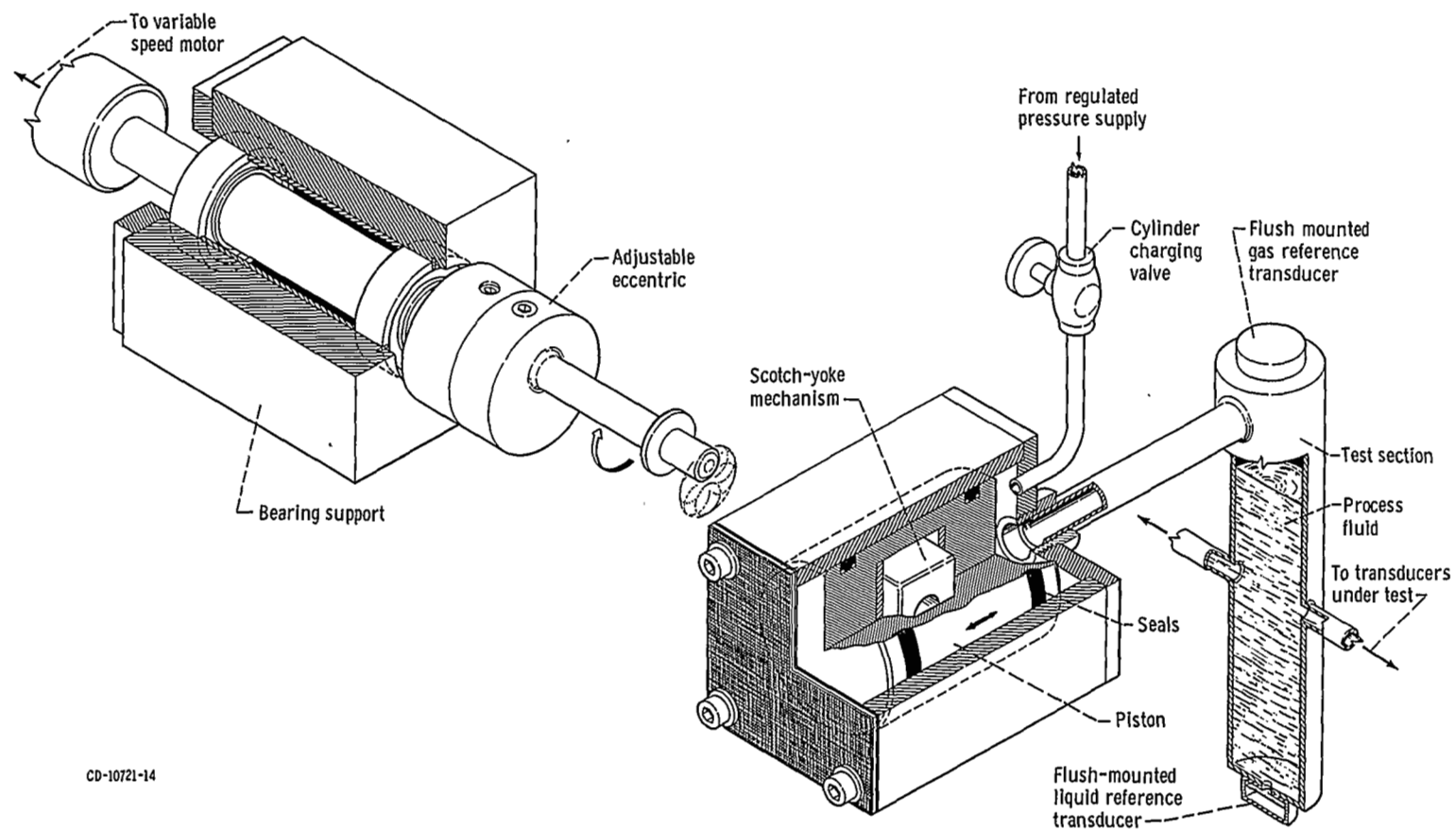
1. For the slack-bellows transducer systems, the natural frequency was found to decrease with increasing standoff tube length. With 0.187-inch- (0.476-cm-) inside-diameter standoff tubes ranging in length from 6 to 24 inches (15 to 61 cm), the natural frequencies ranged from 4.9 to 2.5 hertz, respectively, with mercury and from 18.9 to 10.8 hertz, respectively, with the simulated sodium-potassium mixture (aliphatic petroleum naphtha solvent). For constant standoff tube length, natural frequency varied inversely as the square root of the density; and for constant density, natural frequency varied inversely as the square root of the tube length. The maximum deviation between the natural frequencies obtained experimentally and theoretically (for both fluids) was less than 10 percent.

2. For the slack diaphragm with capillary tube transducer systems, the frequency response characteristics were not affected by either standoff tube length or the fluid used.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 5, 1970,
120-27.

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2. Schweppe, J. L.; Eichberger, L. C.; Muster, D. F.; Michaels, E. L.; and Paskusz, G. F.: Methods for the Dynamic Calibration of Pressure Transducers. Monograph 67, National Bureau of Standards, Dec. 12, 1963.
3. Anon.: Dynamic Response Testing of Process Control Instrumentation. Standard S26, Instrument Society of America, 1968.



CD-10721-14

Figure 1. - Exploded view of variable-frequency sinusoidal pressure generator and test section.

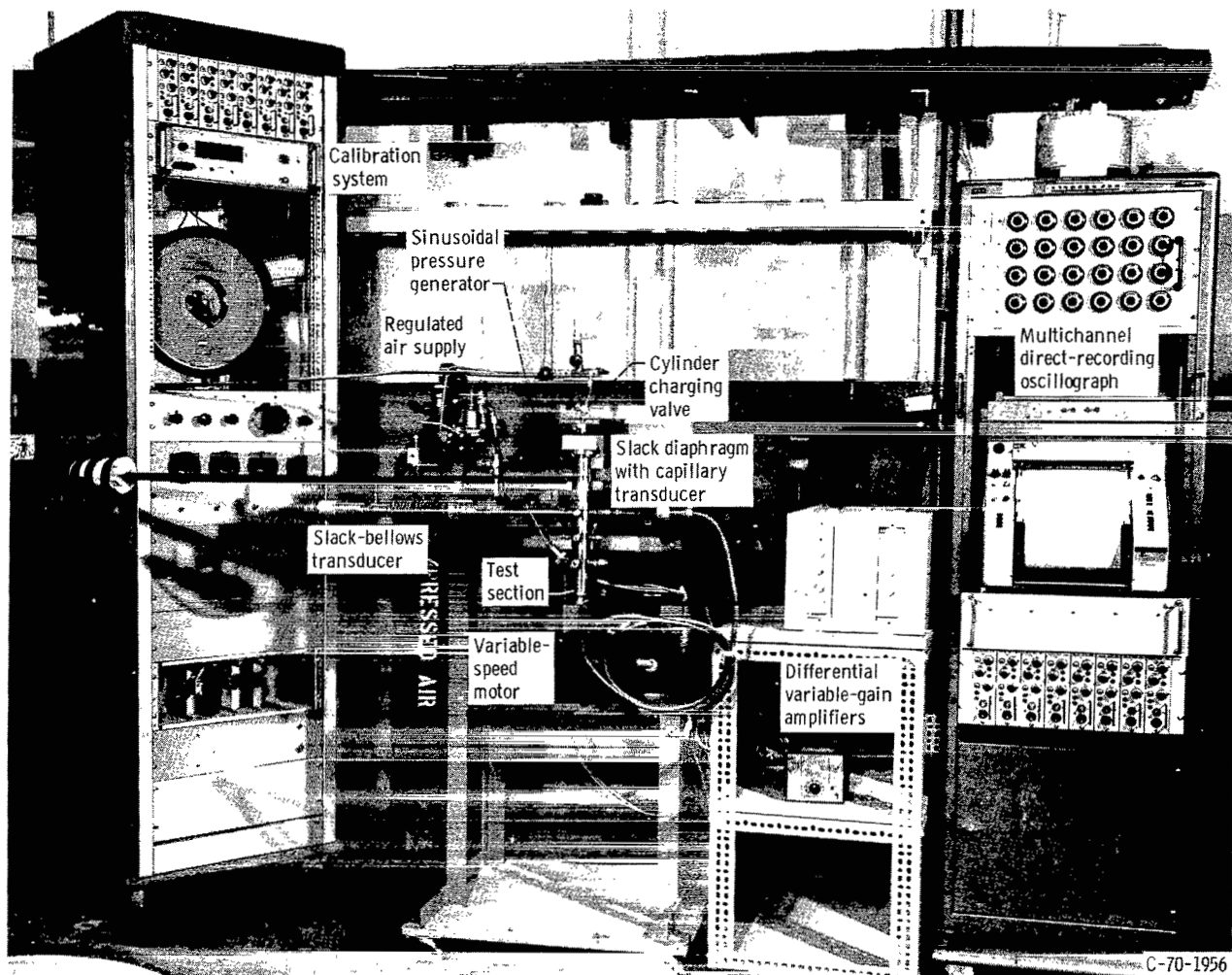
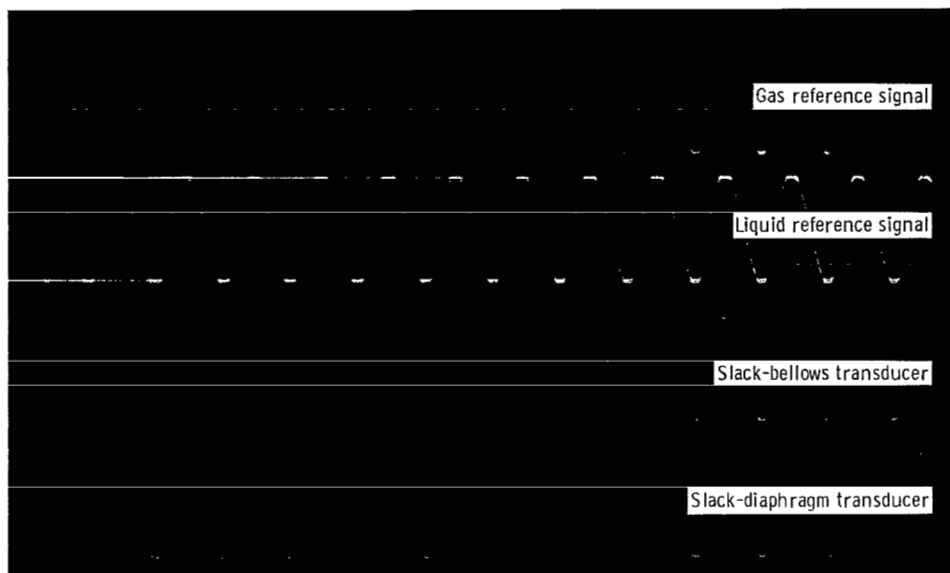
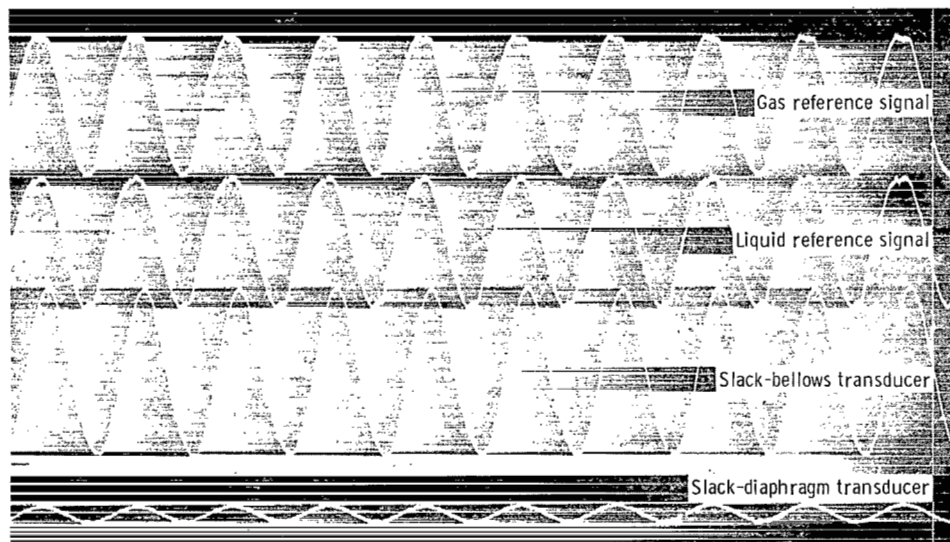


Figure 2. - Test facility used to obtain frequency response.



(a) Oscilloscope trace at starting frequency (0.05 Hz).



(b) Oscilloscope trace at higher frequency (10 Hz).

Figure 3. - Typical oscilloscope traces of transducer electrical output signals.

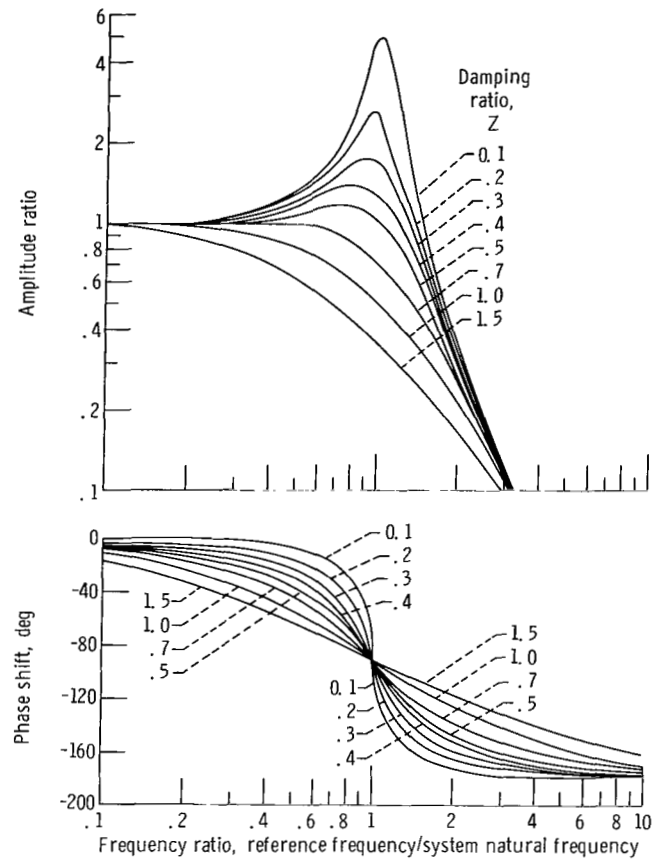


Figure 4. - Frequency response for second-order systems.

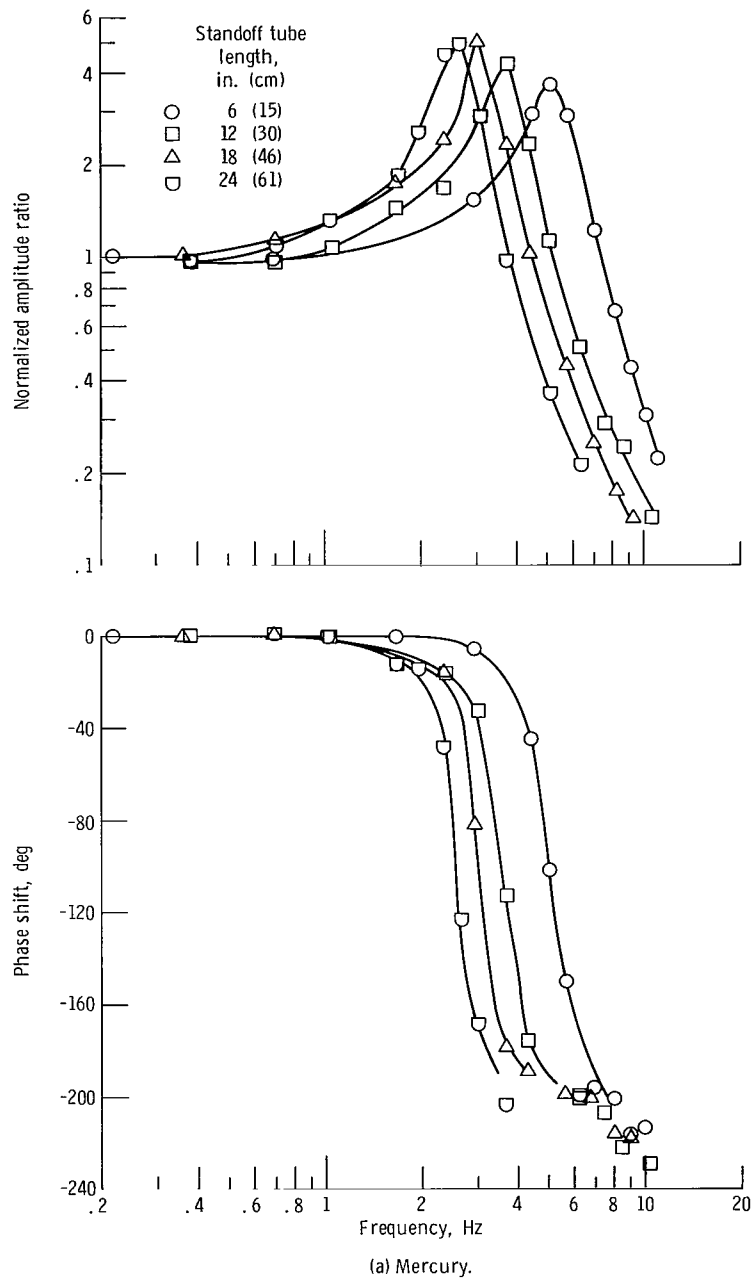
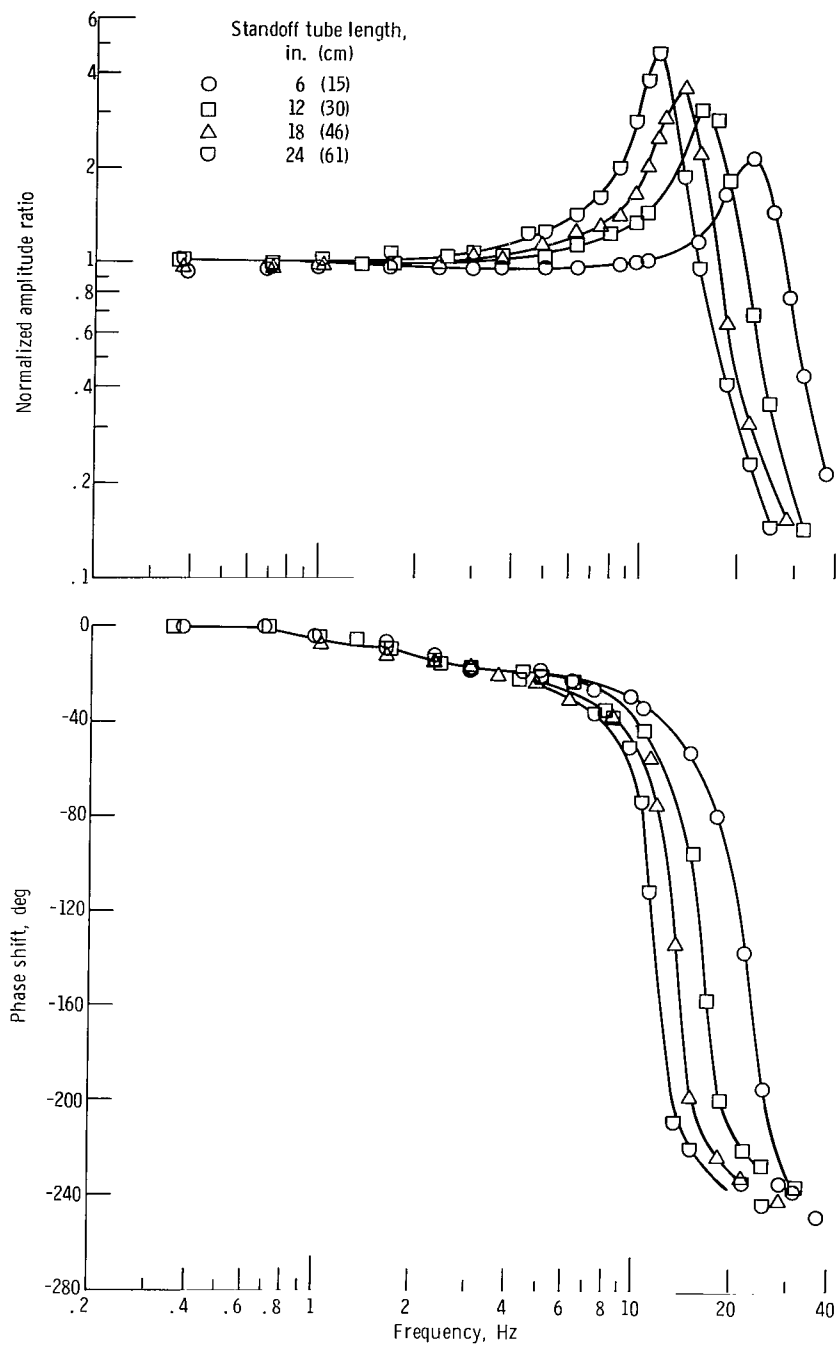


Figure 5. - Frequency response of liquid-filled slack-bellows pressure transducer systems.



(b) Aliphatic petroleum naphtha solvent (simulated NaK).

Figure 5. - Concluded.

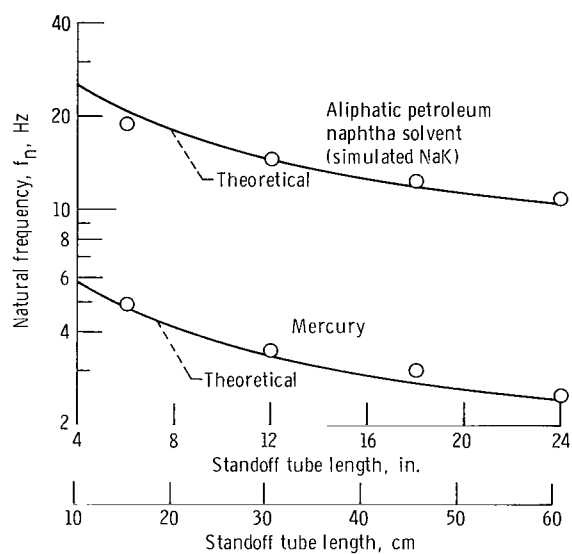


Figure 6. - Natural frequency of liquid-filled transducer systems as function of standoff tube length.

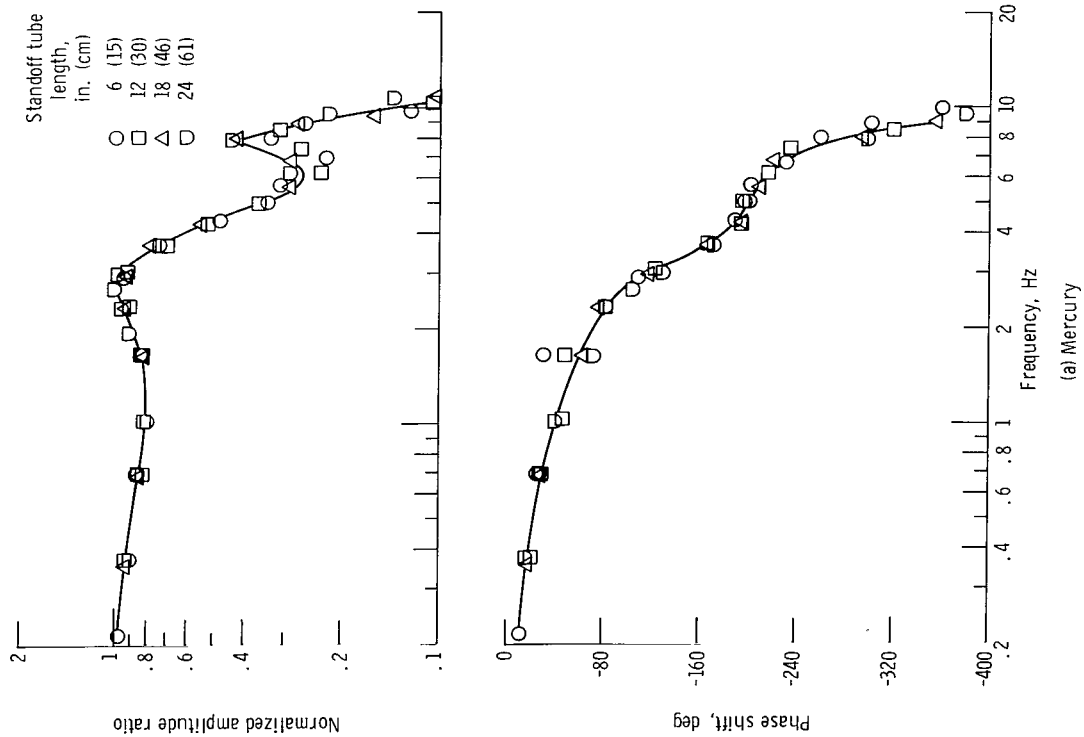


Figure 7. - Frequency response of liquid-filled slack diaphragm with capillary tube pressure transducer systems.

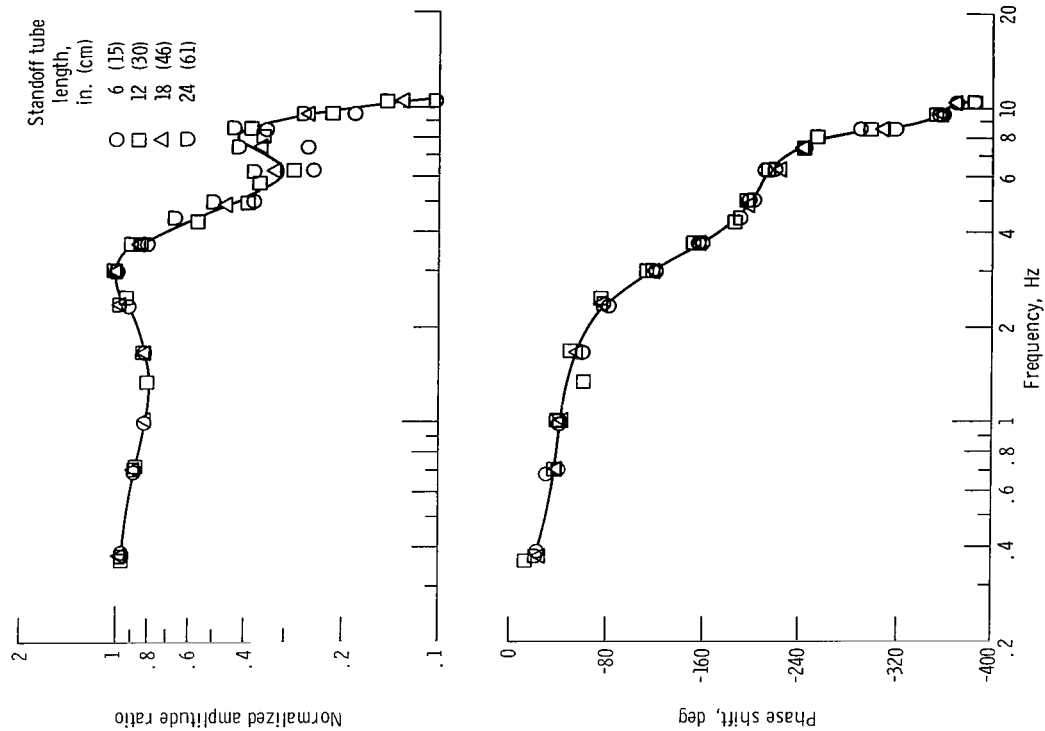


Figure 7. - Concluded.



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